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X-ray binaries powered by massive stellar black holes

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Abstract. The mass of stellar black holes (BHs) is currently thought to be in the 3 − 20 $M_\odot$ range, but is highly uncertain: recent observations indicate the existence of at least one BH with mass > 20 $M_\odot$. The metallicity of the progenitor star strongly influences the mass of the remnant, as only metal-poor stars can have a final mass higher than ~ 40 $M_\odot$, and are expected to directly collapse into BHs with mass > 25 $M_\odot$. By means of N−body simulations, we investigate the formation and evolution of massive stellar BHs (MSBHs, with mass > 25 $M_\odot$) in young dense star clusters. We study the effects of MSBHs on the population of X-ray sources.

Key words. black hole physics – methods: numerical – stars: binaries: general – stars: kinematics and dynamics – galaxies: star clusters: general – X-rays: binaries.

1. Introduction

The mass spectrum of stellar black holes (BHs) is currently thought to be in the 3 − 20 $M_\odot$ range, but is highly uncertain. Dynamical mass estimates are available only for a few tens of BHs, hosted in X-ray binaries (see table 2 of Özel et al. 2010 for one of the most updated compilations). In the Milky Way, the dynamically measured BH masses range from ≈ 4 to ≈ 15 $M_\odot$. BHs with mass > 15 $M_\odot$ were found in some nearby galaxies. In Table 1 and in Fig. 1, we report a compilation of BH masses from the literature. All of them come from dynamical measurements, and are among the best constrained values. Three out of five BHs in nearby galaxies (last 5 lines of Table 1) have mass $\gtrsim 15$ $M_\odot$. In the case of IC 10 X-1, the BH mass can be as high as ≈ 30 $M_\odot$ (e.g., Prestwich et al. 2007).

Which factors can affect the BH mass? Theoretical models (e.g. Heger et al. 2003; Mapelli et al. 2009; Zampieri & Roberts 2009; Belczynski et al. 2010; Fryer et al. 2012) indicate that the metallicity (Z) of the progenitor star can significantly influence the mass of the BH. In particular, a massive star can collapse quietly into a BH (i.e. without supernova or with a faint supernova), if its final mass is sufficiently high (≈ 40 $M_\odot$, Fryer 1999). Massive metal-poor stars lose less mass by stellar winds than metal-rich stars (e.g. Vink et al. 2001), and thus are more likely to have a final mass $\gtrsim 40$ $M_\odot$.

The mass of a BH born from direct collapse is expected to be very close to the final mass of the progenitor star: it can significantly exceed 25 $M_\odot$, depending on the metallicity. Interestingly, the stellar BH with the highest dynamically measured mass is hosted in the metal-poor galaxy IC 10 ($Z = 0.22$ $Z_\odot$, from an electron-temperature based calibration of spectra of HII regions, assuming $Z_\odot = 0.019$).

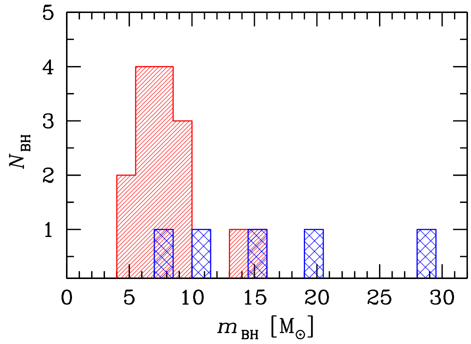

Fig. 1. Distribution of BH masses derived from dynamical measurements. The BH masses were taken from the literature and are listed in Table 1. Hatched red histogram: Milky Way BHs; cross-hatched blue histogram: BHs in nearby galaxies.

In the following, we call massive stellar BHs (MSBHs) those BHs with mass > 25 M$_\odot$, born from a quiet collapse. The existence of MSBHs in the nearby Universe may be crucial for our understanding of X-ray sources. The scenario of X-ray binaries powered by MSBHs was recently proposed to explain a fraction of the ultraluminous X-ray sources (ULXs, i.e. point-like X-ray sources with luminosity, assumed isotropic, higher than 10^{39} erg s^{-1}, e.g. Mapelli et al. 2010). In this paper, we study (by means of N−body simulations) the formation and evolution of MSBHs in young star clusters (SCs), and we investigate their importance for the population of accreting binaries.

2. Simulations

We simulate young SCs, as (i) most stars form in SCs (Lada & Lada 2003), and (ii) high-mass X-ray binaries and ULXs are often associated with OB associations and with young SCs (e.g. Zezas et al. 2002; Soria et al. 2005; Swartz et al. 2009).

Most SCs are collisional environments: their two-body relaxation timescale is short with respect to their lifetime. Thus, binaries in SCs undergo a number of three-body encounters, i.e. close encounters with single stars. Three-body encounters affect the population of accreting binaries, in collisional environ-

Table 1. Compilation of BH masses from dynamical measurement.

Name	Type[a]	m_{BH} (M$_\odot$)	Ref.[b]
GRO J 0422+324.3	SPT	3.7 − 5.0	(1)
A 0620-003	SPT	6.6 ± 0.2	(2)
GRS 1009-45	SPT	3.6 − 4.7	(1)
XTE J 1118+480	SPT	6.5 − 7.2	(1)
GS 1124-683	SPT	6.5 − 8.2	(1)
GS 1354-64	LPT	7.9 ± 0.5	(3)
4U 1543-47	LPT	9.4 ± 1.0	(2)
XTE J 1550-564	LPT	9.1 ± 0.6	(2)
GRO J 1655-40	LPT	6.3 ± 0.3	(2)
H 1705-250	SPT	5.6 − 8.3	(1)
SAX J 1819.3-2525	LPT	7.1 ± 0.3	(2)
GRS 1915+105	LPT	14 ± 4	(4)
Cyg X-1	PS	14.8 ± 1.0	(5)
GS 2000+251	SPT	7.1 − 7.8	(1)
GS 2023+338	LPT	$9.0^{+0.2}_{-0.6}$	(6)
IC 10 X-1	PS	24 − 33	(7)
NGC300 X-1	PS	20 ± 4	(8)
M33 X-7	PS	15.65 ± 1.45	(9)
LMC X-3	PS	5.9 − 9.2	(1)
LMC X-1	PS	10.91 ± 1.54	(10)

[a]SPT (LPT): short- (long-) period transient; PS: persistent source. See Özel et al. (2010). [b]References: (1) Orosz (2003), and references therein; (2) Özel et al. (2010), and references therein; (3) Casares et al. (2009); (4) Harlaftis & Greiner (2004); (5) Orosz et al. (2011); (6) Khargharia et al. (2010); (7) Prestwich et al. (2007); (8) Crowther et al. (2010); (9) Orosz et al. (2007); (10) Orosz et al. (2009).

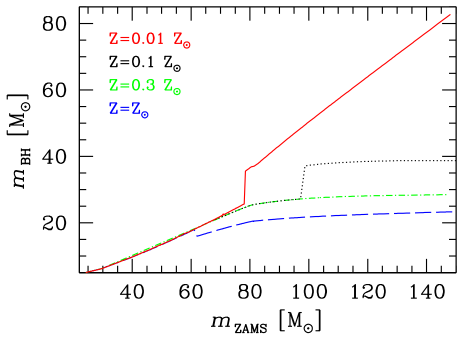

Fig. 2. Mass of the BH (m_{BH}) versus ZAMS mass (m_{ZAMS}) of the progenitor star, for a population of single stars. Solid red line: 0.01 Z$_\odot$; dotted black line: 0.1 Z$_\odot$; dashed blue line: 1 Z$_\odot$.

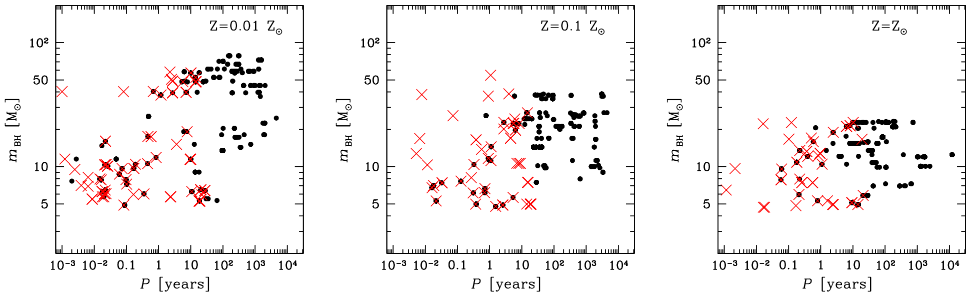

Fig. 3. Mass of the BH versus orbital period, for the simulated BH binaries, during the accretion phase. Filled circles: wind-accretion systems; red crosses: RLO systems. From left to right: 0.01 Z$_\odot$, 0.1 Z$_\odot$, 1 Z$_\odot$.

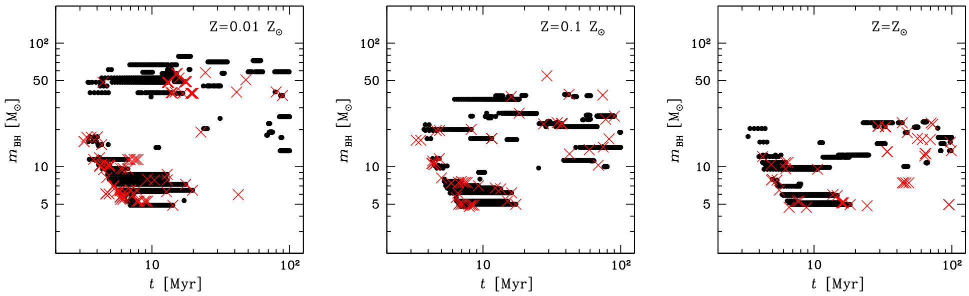

Fig. 4. Mass of the BH versus time elapsed since the beginning of the simulation, for the BH binaries, during the accretion phase. The symbols are the same as in Fig. 3.

ments. For example, three-body encounters can change the semi-major axis of a binary, triggering mass transfer. Furthermore, a BH that was born from a single star can become member of a binary, by replacing one of its former members through a dynamical exchange.

We perform N-body simulations of SCs using the Starlab public software environment (Portegies Zwart et al. 2001). We modified Starlab, to include metal-dependent stellar evolution and recipes for stellar winds by Vink et al. (2001; see also Mapelli et al. 2013 for more details on the code). We simulated young intermediate-mass SCs, generated according to a multi-mass King model, with total mass $M_{\rm TOT} = 3000 - 4000$ M$_\odot$, initial core radius $r_{\rm c} = 0.4$ pc, concentration $c = 1.03$. The stars in the SC follow a Kroupa (2001) initial mass function. We include a fraction $f_{\rm b} = 0.1$ of primordial binaries in the initial conditions. We consider three different metallicities: $Z = 0.01$, 0.1 and 1 Z$_\odot$. We ran 100 realizations of the same SC (by changing the random seed) for each Z, to filter out the statistical fluctuations.

3. Results

The simulations provide information about the formation and evolution of X-ray binaries, powered by both Roche lobe overflow (RLO) and wind accretion. Fig. 3 shows the mass of the BH versus the orbital period of RLO (crosses) and wind-accreting (circles) binaries. It is apparent that accreting binaries at low metallicity can be powered by MSBHs: 10 − 20 per cent (5 − 10 per cent) of all MSBHs power wind-accreting (RLO) systems. Interestingly, the vast majority ($>$ 90 per cent) of accreting binaries powered by MSBHs underwent at least one dynamical exchange before starting the accretion. In most cases, the MSBH formed from a single star and then became member of a binary via exchange. This is in agreement with the fact that the rate of three-body encounters (and especially of exchanges) scales with the mass of the involved objects.

Fig. 4 gives information about when a binary starts wind accretion or RLO, with respect to the time elapsed since the beginning of the simulation. Binary systems powered by low-mass BHs tend to start the RLO phase earlier than those powered by MSBHs. The reason is that the RLO phase in systems powered by low-mass BHs is driven by the stellar evolution of the companion, while in systems powered by MSBHs it is mainly a consequence of dynamical exchanges, which occur on a longer timescale. Fig. 2 shows the mass spectrum of BHs in our simulations, as a function of the zero-age main sequence (ZAMS) mass of the progenitor star. The effect of metallicity is apparent: no BHs with mass $> 25\ M_\odot$ form at solar metallicity from the evolution of single stars, while MSBHs with mass as high as $\sim 80\ M_\odot$ can form at $Z = 0.01\ Z_\odot$.

4. Conclusions

In this paper, we investigated the importance of MSBHs for the population of accreting binaries in young SCs. We showed that $\sim 5-10$ per cent of all the simulated MSBHs power RLO systems. The vast majority of accreting binaries powered by MSBHs underwent at least one dynamical exchange before starting the accretion. Instead, the number of accreting MSBHs in unperturbed primordial binaries is negligible. The key result of our simulations is that MSBHs are efficient in powering X-ray binaries through dynamical evolution. This result indicates that MSBHs can power X-ray binaries in low-metallicity young SCs, and is very promising to explain the association of many ultraluminous X-ray sources with low-metallicity and star forming environments.

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